Abstract

A bio- and haemocompatible packaging strategy is proposed for an implantable pressure sensor for continuous direct blood pressure monitoring. A commercial sub-millimeter piezoresistive sensor was attached to an alumina substrate and a double coating of PDMS and parylene-C was applied. The packaged device has dimensions of 2.6x3.6x1.8 mm. A surface modification technique using O2 and SF6 plasma has been employed to tune the haemocompatibility of the packaged sensor. By enhancing the intrinsic hydrophobicity of parylene it is possible to increase plasma proteins adsorption and minimize platelets adhesion on the surface. Contact angle measurements were performed on parylene-coated PDMS samples after plasma treatment, using water and whole pig blood. A maximum contact angle of 134° has been achieved. The influence of different plasma exposure times on the surface wettability has been investigated. To study the stability of the plasma treated surfaces, the contact angle was measured immediately and at regular intervals

Introduction

The direct measurement of arterial pressure offers a stable and accurate solution in a variety of clinical applications where long term, continuous monitoring of blood pressure is desired. However, the long term application of biomaterials in direct contact with blood poses a big challenge to the success of the implant because of the complex mechanism of activation of the blood coagulation system. This work presents an intravascular pressure sensor, specifically designed to be embedded in the inflow and outflow connectors of a left ventricular assist device (LVAD), intended to monitor the pressure rise in the heart pump. Because of its superior mechanical and electrical properties, parylene-C has been selected as the outmost coating layer of the device. In the last years there has been an increased interest in the use of parylene-C as a packaging material for blood contacting devices. In 2002, Weisenberg [1] suggested that parylene-C possesses haemocompatibility similar to Polyurethane, but to date its long term performance in the blood stream has not been fully investigated. Several authors [2-3] reported high adsorption of plasma proteins onto parylene surfaces, due to strong hydrophobic interactions between proteins and the hydrophobic films. Albumin, together with other plasma proteins, has an inhibitory effect on platelet aggregation. In this perspective, enhancing parylene-C hydrophobicity could greatly improve the sensor haemocompatibility.

Sensor design and packaging

A piezoresistive pressure sensor from Silicon Microstructures Inc. (SM5108C), in die form, was mounted on an alumina substrate using a biocompatible epoxy from Epoxy technology (EPO-TEK 302-3M). The contact pads on top of the sensor were connected to the contact pads on the alumina substrate by means of gold wirebonds. To provide additional resistance to mechanical agitation, the wirebonds were carefully embedded in medical grade epoxy, avoiding coverage of the sensitive membrane. Using a molding technique, the sensor was covered with a layer of medical grade PDMS (Nusil MED-4211). Finally a 4 µm thick layer of parylene-C was deposited on the device via chemical vapor deposition to protect it from aggressive body fluids. Indeed, together with the need for a non-thrombogenic material, this protection forms the biggest

challenge for devices that are exposed to blood . A schematic view of the sensor is presented in Fig.1a, together with a packaged device before (Fig.1b) and after (Fig.1c) integration in the LVAD titanium connector.

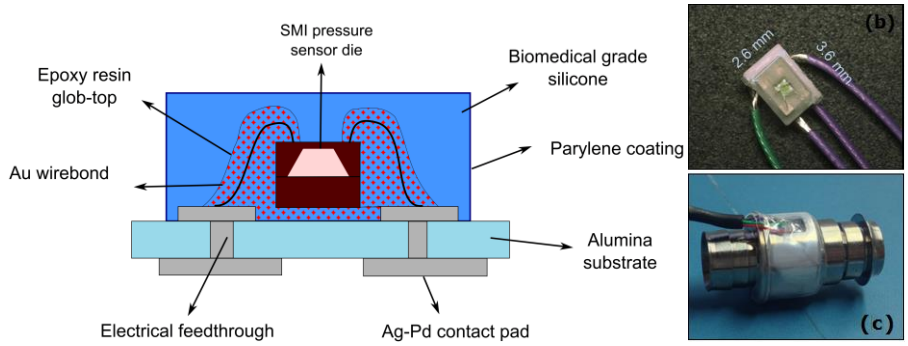

Fig. 1. (a) Schematic overview of the sensor and biocompatible packaging strategy; (b) Packaged sensor; (c) Sensorized LVAD connector

Parylene-C plasma treatment

The surface wettability of biomaterials is a parameter of paramount importance in blood contacting devices, since it greatly influences blood proteins and specifically albumin adsorption. Hydrophilic and hydrophobic interactions drive the attraction of polar and nonpolar groups of the albumin chain to substrates with different wetting behavior. Several studies suggest that Bovine Serum Albumin (BSA) adsorbs more easily on highly hydrophobic substrates [4,5], others [2] demonstrated that increasing the wettability of parylene-C surfaces, by oxygen plasma treatment, results in lower albumin adsorption. In this work, the intrinsic hydrophobicity of parylene-C has been enhanced with a low power plasma treatment like the one proposed by [6]. Rectangular PDMS samples with dimensions of 1x1 cm were prepared using MED-4211 and covered with a 10 µm thick layer of parylene-C. The samples were exposed to 10 minutes of O2 plasma, followed by 1 minute of SF6 plasma. All treatments were performed with an RF power of 100 W and a gas flow of 100 sccm. The static contact angle of DI water and pig whole blood was measured on PDMS and on parylene-C before and immediately after the treatment. A 3 µl droplet was released on the sample using a vertical syringe and digital images were recorded. The acquired pictures were then analyzed using the software ImageJ to determine the contact angle. Fig.3 shows the results of this analysis. Each measurement point is the average value of the contact angle measured for at least three different droplets. The plasma treated parylene-C surface exhibited a stronger hydrophobicity with a contact angle that increased from 94° to 134° for water and from 92° to 130° for pig blood .

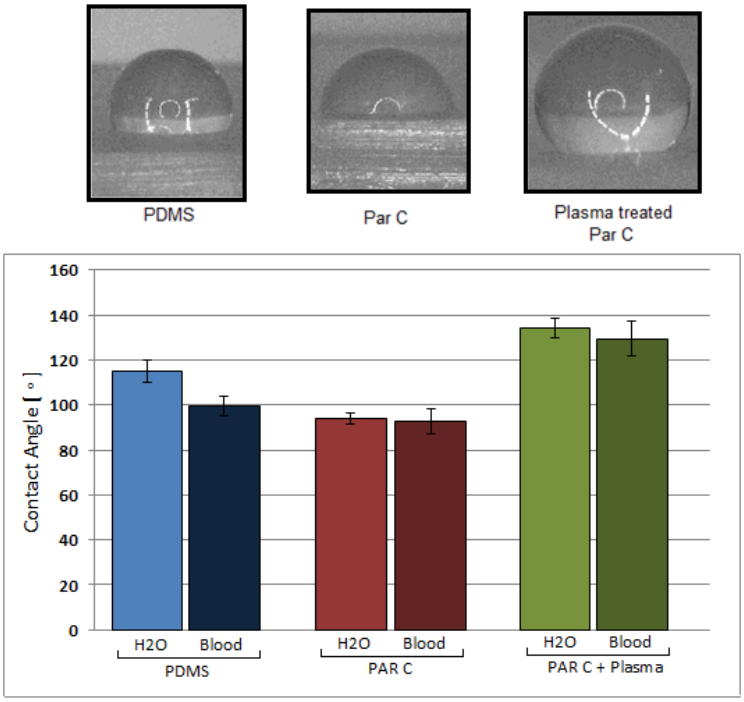

Fig. 2. Measured contact angle for DI water and pig whole blood on PDMS and parylene-C before and after plasma treatment.

This result can be explained by mainly two factors: the physical roughening of the surface during the initial O2 plasma treatment, and the chemical modifications resulting from the introduction of fluorinated groups during the consecutive SF6 plasma treatment [6]. When adopting this technique in long term implants, it is important to assess the stability over time of the surface hydrophobicity. Therefore, a set of six microscope slides was coated with a 10 µm thick layer of parylene and submitted to the six different plasma treatments mentioned in Table 1

Table 1. Duration of O_2 and SF_6 plasma treatment on parylene C coated glass

Sample	O_2 [s]	SF_6[s]
1	0	0
2	30	30
3	30	60
4	30	120
5	60	30
6	120	30

The contact angle was measured immediately and every 24 hours for 15 days. Every day, before each measurement, nitrogen was blown onto the samples to remove dust particles and every 3 days the samples were rinsed using DI water. The results of this measurement are illustrated in Fig.3.

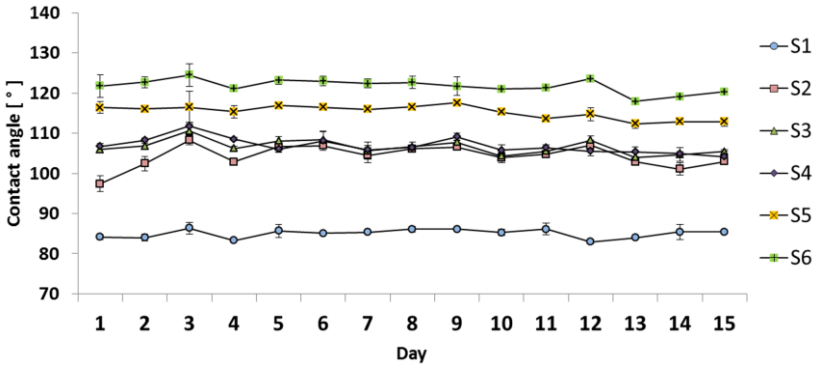

Fig. 3. Stability of parylene-C surfaces during the first 15 days from the plasma surface treatment.

Despite some minor variations in the contact angle, that can be attributed to contaminants gathering on the specimen surface, the different samples retained their hydrophobicity over the investigated time interval. It is clear that all of the performed treatments increase the hydrophobicity of parylene. As no substantial increase in the contact angle was registered between samples 2, 3 and 4, when only increasing the SF6 treatment time, we conclude that the surface is saturated with fluorine groups relatively quickly. On the other hand, the significantly higher hydrophobicity registered for samples 5 and 6, exposed to a longer O2 plasma treatment, indicates a stronger influence of the surface roughening.

Conclusion

An intravascular pressure sensor was designed and fabricated. A bio- and haemocompatible packaging strategy was proposed, based on a double coating layer of PDMS and parylene-C. Parylene intrinsic hydrophobicity was enhanced using a low power plasma treatment. The stability of the hydrophobic surfaces was proven up to 15 days from the treatment. While chemical alterations to the surface are important to the hydrophobicity, the mechanical roughening appears to be the dominating factor. Studying the adsorption of albumin and other plasma proteins could aid the further assessment of plasma treatment material haemocompatibility.

Acknowledgements

Research was performed within the SensorART project, funded by the European Communities Seventh Framework Programme (FP 7/2007-2013) under the grant agreement No. 248763, and the ERC-2013-AG, μThalys, grant agreement No. 340931

References

[1] Weisenberg BA, Mooradian DL, Hemocompatibility of materials used in microelectromechanical systems: platelets adhesion and morphology in vitro, J. Biomed Mater Res (2002) 283–91.

[2] Tracy Y. and Vikramaditya G., Cell and Protein Compatibility of Parylene-C Surfaces, Langmuir, 23 (2007), 11718–11725.

[3] Bogdan Walkowiak and Wieslawa Okroj., Interaction of Poly(p-Xylylene)with biological objects, Polymer Preprints, (2008) 937.

[4] Lee J.N., Jiang X., et al., Compatibility of mammalian cells on surfaces of poly(dimethylsiloxane), Langmuir 20 (2004) 11684-11691.

[5] Lee, Jin Ho, and Hai Bang Lee, A wettability gradient as a tool to study protein adsorption and cell adhesion on polymer surfaces, Journal of Biomaterials Science, Polymer Edition 4.5 (1993) 467-481.

[6] Xiao-Peng Bi and Brian Park Crum, Super Hydrophobic Parylene-C Produced by consecutive O2 and SF6 Plasma Treatment, J. of microelectromechanical systems, 23 (2014) 628-635